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TNO-report **IZF 1993 B-6**

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ON THE DEVELOPMENT OF MOTOR CHUNKS AND CONCURRENT PROCESSING IN A STRUCTURED CONTINUOUS KEYPRESSING TASK

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Number of pages: 24

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Title:	On the development of motor chunks and concurrent processing in a structured continuous keypressing task
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Institute:	TNO Institute for Perception Group: Skilled Behavior
Date:	June 1993
DO Assignment No.:	B92-26
No. in Program of Work:	788.2

SUMMARY

This report describes an experiment designed to assess the effects of practice in performing a structured sequence of keypresses. The task consisted of pressing a sequence of nine keys with nine fingers, each in response to a corresponding stimulus. Each response was followed by a response-stimulus interval (RSI), which sometimes was zero ms, before the next stimulus was presented. Upon completion of one sequence, production of the identical sequence was immediately repeated. One group of 18 subjects—the 333 group—practiced with three regularly spaced, non-negligible, response-stimulus intervals (RSIs) while the remaining RSIs were zero. This divided the sequence into three groups of three keypresses each. Another group of 18 subjects—the 45 group—practiced with two non-negligible RSIs partitioning the sequence into a four- and a five-key group. These conditions were coined structured conditions. On occasion all subjects carried out a condition in which all RSIs were zero. This was the unstructured condition. The results show that interkey times in this condition clearly reflected the position of the long RSIs in the structured condition. This suggests that motor chunks had developed in the structured condition which were also used in the unstructured condition. More detailed analyses suggest that preparing one chunk concurred with execution of the preceding chunk in the unstructured and probably also in the structured condition. Concurrent preparation of the next chunk slowed down execution of the preceding chunk in the unstructured condition. In the structured condition it concealed effects of chunk-size on initiating each chunk (i.e. the complexity effect).

Rap.nr. IZF 1993 B-6

Instituut voor Zintuigfysiologie TNO
Soesterberg

Over de ontwikkeling van motor chunks en parallelle informatieverwerking in een gestructureerde continue toetsdruktaak

W.B. Verwey en Y. Dronkert

SAMENVATTING

Dit rapport beschrijft een experiment om effecten van oefening in een gestructureerde toetsdruk-sequentie te onderzoeken. De taak bestond uit het indrukken van negen toetsen met negen vingers, elk in respons op een corresponderende stimulus. Elke respons werd gevolgd door een respons-stimulus interval (RSI) welke soms nul ms was, voordat de volgende stimulus aangeboden werd. Na uitvoering van zo'n sequentie werd dezelfde sequentie direct opnieuw uitgevoerd. Een groep van 18 proefpersonen—de 333 groep—oefende met drie regelmatig verdeelde, niet-verwaarloosbare RSIs terwijl de overige RSIs nul waren. Dit verdeelde de sequentie in drie groepen van elk drie toetsdrukken. Een andere groep van 18 proefpersonen—de 45 groep—oefende met twee niet-verwaarloosbare RSIs welke de sequentie in een vier- en een vijf-toets groep verdeelde. Deze condities werden de gestructureerde condities genoemd. Af en toe werkten proefpersonen in een conditie waarin alle RSIs nul waren: de ongestructureerde conditie. De resultaten laten zien dat de intertoetstijden in deze conditie goed de posities van de lange RSIs in de gestructureerde conditie weergaven. Dit suggereert dat zich motor chunks hadden ontwikkeld in de gestructureerde conditie die ook gebruikt werden in de ongestructureerde conditie. Gedetailleerde analyses suggereren dat voorbereiding voor een chunk samenviel met uitvoering van de voorafgaande chunk. Dit gebeurde in de ongestructureerde, maar vermoedelijk ook in de gestructureerde conditie. Deze overlappende preparatie vertraagde de uitvoering van de voorafgaande chunk in de ongestructureerde conditie. In de gestructureerde conditie verborg overlappende preparatie effecten van chunk-grootte op de tijd om de responsgroepen te initiëren (het complexity effect).

1 INTRODUCTION

Practice is generally viewed as a major determinant of proficient motor performance. With regard to executing movement sequences there is the classic notion that they are constructed from combining elementary, sometimes innate, motor patterns or chunks (e.g. Book, 1908; Keele, 1986; Lashley, 1951; Miller, Galanter & Pribram, 1960; Paillard, 1960). The reason for executing movement sequences as a concatenation of isolated chunks lies probably in the associated storage and retrieval efficiency (see e.g. Jones, 1981; Newell & Rosenbloom, 1981; Restle, 1970). Yet, despite the long-lasting history of this notion it is still insufficiently clear what exactly determines the development of motor chunks and their typical properties. Sternberg, Knoll, and Turock (1990) listed various features suggestive of the role of motor chunks in sequences. One is that intervals separating successive component actions should be longer across than within chunk boundaries (e.g. Adams, 1984; Reason, 1979; Shaffer, 1976). Another regards invariant execution of a chunk which implies that intervals within chunks should be relatively constant (e.g. Gentner, 1987; Terzuolo & Viviani, 1980). The question remains what the responsible mechanisms are, how such relations develop, and how general they are.

The first purpose of this paper was to examine one way chunking might develop in a multi-finger keypressing task, i.e. by imposing a timing structure during practice. This paradigm was used by Summers and colleagues (Summers, 1975; Summers, Sargent & Hawkins, 1984) who carried out several experiments in which nine keys had to be pressed with nine fingers in response to stimuli which were presented in nine spatially compatible locations. The stimuli were presented in a fixed order and at an experimenter-determined rate. Summers' interest concerned how the timing and sequencing aspects of motor skills are integrated. When a single sequence had been completed it was immediately produced again so that subjects continuously cycled through the nine keypresses. In one condition (the 511 condition in Summers, 1975) the sequence was structured in that it contained three response groups. Each response group started with a 500 ms response-stimulus interval (RSI) preceding the first keypress of the group and two 100 ms RSIs preceding the second and third keypresses. Following extensive practice, the subjects were instructed to reproduce the sequence as fast as possible in an unstructured condition without any differences in RSI, and without any requirement to adhere to the original timing structure. The results showed that the timing structure was maintained during 10 subsequent blocks of unstructured trials in that the interkey times that had been preceded by a 500 ms RSI during practice were about twice as long as those that had been preceded by a 100 ms RSI. Summers proposed that relative timing becomes an integral part of the motor program representation. He argued that the long intervals were about twice as long as the short ones due to a "natural" tendency to adhere to 1:1 or 2:1 ratios. These ratios are stable since rhythms are symmetrical, hierarchical structures of time patterns in which, basically, all elements in the output occur at equal time intervals (Martin, 1972). When the number of events in a sequence deviates from a power of two, "blank" elements—i.e. covert sequence elements—are inserted at appropriate points in order to represent the sequence as a binary tree with equal intervals between successive elements. Insertion of a blank leads to the 2:1 ratio. So, rapid and continuous execution of the 511 sequence without the need to adhere to the timing structure yields the observed 2:1:1 ratio because a blank is inserted at the position of the 500 ms RSI during practice in order to arrive at a binary tree representation consisting of four elements.

The suggestion that performance in the rapid unstructured condition relies on the same clock-like triggering mechanism as in relatively slow rhythm production (Martin, 1972) is not a necessary deduction. Alternatively, the interkey times in the unstructured sequence might have been determined by the duration of the processes involved in producing the responses. Summers' (1975) finding, then, that the original timing structure returned in the unstructured condition could suggest that the timing structure had partitioned the sequence into separate motor chunks, which had become so robust that they were also used when not explicitly required in the unstructured condition. This chunking hypothesis presumes hierarchical sequence execution (Sternberg et al., 1990) in that chunks are selected and programmed as a whole on a higher level while at a lower level individual elements of the chunk are retrieved and executed from a motor buffer (Henry & Rogers, 1960; Sternberg, Monsell, Knoll & Wright, 1978). This is consistent with Sternberg et al.'s (1990) contention that there are two hierarchical levels in speech and typing. A main purpose of this paper was to investigate the alternative hypothesis that imposing a timing structure governs the development of motor chunks rather than inducing a natural rhythm.

The chunking hypothesis suggests that the 2:1 ratio observed by Summers (1975) in the unstructured condition was merely incidental. The ratio would actually depend on two factors. First, the time for initiating a *single* movement sequence is known to be influenced by the number of units in the sequence (Henry & Rogers, 1960; Sternberg et al., 1978), even in the absence of uncertainty about timing and keys (Canic & Franks, 1989). This has been called the *complexity effect*. If producing response groups in structured multi-finger keypressing sequences is similar to producing keypressing sequences in isolation, one may expect a complexity effect at the start of each group. This would be a strong indication that the timing structure during practice invokes partitioning of the sequence into smaller parts, each of which relies on the mechanisms proposed for isolated sequences (Henry & Rogers, 1960; Sternberg et al., 1978). Basically, the complexity effect should show up in structured as well as in unstructured conditions.

A second factor affecting the ratio in unstructured conditions is *practice*. The chunking hypothesis assumes that the impact of chunking will increase because subjects will tend to select and program the chunk more and more as a whole prior to its initiation. The times between successive keys within a response group would decrease more with practice than the time preceding a response group which has the effect that the ratio increases. Accordingly, it was investigated whether the complexity effect, as observed when producing single movement sequences, also occurred when starting a response group, and whether the ratio of times preceding and within response groups in an unstructured condition increased with practice.

Finally, there are indications that preparing a next keypress may concur with execution of earlier keypresses. These preparatory processes involve selection (Verwey, submitted) as well as motor programming (Garcia-Colera & Semjen, 1987, 1988; Rosenbaum, Hindorff & Munro, 1987; Van Donkelaar & Franks, 1991; Verwey, in press-2). The extent of concurrence depends on factors like practice, execution rate, and the number of units in the preceding sequence (Canic & Franks, 1989; Hulstijn & Van Galen, 1983; Verwey, submitted). This could imply that the complexity effect may be concealed in the unstructured condition since preparation of a group may concur with execution of the preceding group. As a consequence, then, execution of that preceding response group would be delayed (Portier, Van Galen & Meulenbroek, 1990; Verwey, in press-2). Recent findings by Verwey (submitted) suggest that the extent of concurrent processing increases with the number of preceding keypresses. This suggests that the time required for initiating a response group in the unstructured condition would not simply increase with its own size, but could even decrease as the size of the preceding group is longer.

The predictions derived from the chunking hypothesis were tested in Summers' (1975) type of keypressing task. The stimulus-response times within a response group were compared in structured and in unstructured conditions to decide whether, due to concurrent preparation, they are longer in the unstructured condition. This led to the use of zero RSIs within a response group rather than Summers' (1975) 100 ms RSIs. To ascertain that individual response groups were well separated during practice 750 ms rather than 500 ms intergroup RSIs were used. In the 333 condition, subjects practiced a sequence in which the long RSIs were located so that there were three groups of three keypresses each (the sequence also started with a long RSI). In the 45 condition, another group of subjects practiced the same total sequence which now contained two long RSIs partitioning the sequence into a four- and a five-key group. Finally, some trial blocks had an unstructured condition in which all RSIs were zero so that no timing structure was imposed.

Presumably, the timing structure in the 333 sequences determines the duration of the response times in the unstructured condition in a similar way as reported by Summers (1975) for his 511 condition. Although the present RSIs were 750 ms rather than Summers' (1975) 500 ms the natural rhythm hypothesis still predicts that in the unstructured condition ratios between response times should approach 1:1 and 2:1 for individual subjects. Only if different partitioning patterns would occur across subjects the average ratios could be between 1:1 and 2:1 but they should never exceed 2:1. The natural rhythm hypothesis does not indicate how the 45 sequence will be partitioned. Several options are conceivable. For instance, the entire sequence might be represented by a binary tree or separate groups might be represented by binary trees. As a consequence, it is likely that individual subjects will adopt different tree representations and, hence, response times may be about similar irrespective of their location[1].

The chunking hypothesis, on the other hand, predicts that the original timing structure will be reflected in the response times of both the unstructured 333 and 45 condition. The ratios between response times preceding a response group and those within a response group in the unstructured condition need not asymptote at 1:1 and 2:1. Instead, they should increase with practice and they should be larger as the subsequent response group is longer (complexity effect) and the preceding response group is smaller (concurrent preparation).

2 METHOD

2.1 Tasks

A block started with a written instruction to position the left little, ring, middle, and index finger on the z, d, f, g keys of an ordinary PC keyboard and the right thumb, index, middle, ring and little finger on the space bar, j, k, l, and / keys, respectively. These assignments were chosen so that each finger could easily press a separate key (Fig. 1).

Q W E R T Y U I O P

A S $\underline{D}_2$ $\underline{F}_3$ $\underline{G}_4$ H $\underline{J}_5$ $\underline{K}_6$ $\underline{L}_7$;

$\underline{Z}_1$ X C V B N M , . $\underline{/}_8$

$\underline{\text{s p a c e b a r}}_9$

Fig. 1 Layout of the letter-keys on an ordinary PC keyboard. Underlined keys and the space bar were operated by nine different fingers. Indices denote location numbers which are used in the text to indicate response order.

The computer screen displayed white outlines of nine squares in the same spatial arrangement as the assigned keys. The task started when one of the nine squares became homogeneously green as if a light had been turned on. Subjects respond-

[1] This is probably what happened in Summers' (1975) 551 condition where two long RSIs were followed by one short RSI. In terms of the chunking hypothesis this timing structure did not impose a fixed partitioning pattern so that, due to inter- and intra-individual differences, no clear grouping structure evolved.

ed by pressing the corresponding key, whereupon the green content disappeared as if the light had been turned off. After a predetermined response-stimulus interval (RSI) one of the other eight squares turned green which was again followed by pressing the corresponding key. In this way a sequence of nine keypresses was carried out in which each of the nine keys was pressed once. Immediately upon completion of the nine-key sequence, the next trial started which involved the same sequence of nine keypresses.

The RSIs in the structured condition were fixed for either subject group in that the long and zero intervals always occurred at the same positions of the sequence. Subjects in the 333 condition practiced with RSIs: 750-0-0-750-0-0-750-0-0 ms (750 ms between R_9 and R_1, 0 ms between R_1 and R_2 and between R_2 and R_3, etc.). Subjects in the 45 condition practiced the same keypressing sequence with the RSI sequence 750-0-0-0-750-0-0-0-0 ms. In the unstructured condition all RSIs were 0 ms rendering the same task for all subjects.

The same basic sequence was used for all subjects but each of the nine keys functioned as starting key for two subjects of a group. For example, when the stimulus locations are designated 1 through 8 for the fingers from left to right and the right thumb is designated 9 one sequence was 5 9 1 7 4 2 6 8 3 (see Fig. 1). This sequence was also used by Summers (1975) and was carried out by two subjects of each group. Two other subjects of each group executed 9 1 7 4 2 6 8 3 5, etc. In this way, all response times had all between-hand and within-hand transitions. This is important since they are known to affect the time between subsequent keypresses (Kornblum, 1965; Kornbrot, 1989).

2.2 **Procedure**

On the first day a written instruction was handed out to the subjects which briefly introduced the task and the way the computer had to be controlled. Subjects were instructed to type as fast and accurately as possible in order to maximize their score at the end of each block. They were told that the six highest scoring subjects of each group would earn a bonus. All individual blocks were also preceded by a written instruction on the computer monitor, again indicating the sequence to be pressed and, when appropriate, that no long RSIs would occur.

Each subject carried out seven sessions on two consecutive mornings or afternoons. In total 36 subjects took part who were assigned to six groups of six subjects. Within each group three subjects had the 333 and three the 45 condition. On each morning or afternoon two groups were tested in alternation. When one group was tested, the other group relaxed in an adjacent room. This resulted in a 15 minutes rest and test schedule for each subject.

All 14 sessions consisted of 4 blocks of trials. The fourth block of session 1, 3, 5, 8, 10, and 12 had the unstructured condition, all other blocks involved the structured condition. A block had 30 trials. Blocks were separated by a 20 s break.

During a block of trials the keys were always pressed in a fixed order. Hence, the subjects soon knew which key to press next which had the effect that, at least in the structured condition, they could press the key before the RSI had elapsed and the stimulus had been presented. When this happened a "too early" message was presented. An error message also occurred when an incorrect key was pressed or when no key was pressed at all during a 3500 ms interval. In these three situations keypressing could only continue after pressing the correct key.

Each block was followed by display of a score which ranged from 0 to 100 points. The score consisted of a weighted combination of speed and accuracy. The score depended on keying speed in such a way that it still reflected higher speed both early and late in practice. Accuracy affected scoring in that low and high error rates were "punished" by reducing the score: Below 3% and over 6% errors the score was reduced by a fixed amount and the reduction was even larger when errors exceeded 10%. Error rates of less than 3% evoked the instruction to increase keying speed—unless the response time was below 100 ms —whereas error rates of more than 10% elicited the instruction to reduce errors. Response times or error scores were not displayed.

2.3 **Apparatus**

The experiment was conducted on IBM AT compatible (386) computers with NEC multisync color monitors. Stimulus presentation and response registration were controlled through Micro Experimental Laboratory software (MEL; Schneider, 1988). At a typical viewing distance of about 65 cm a square subtended a visual angle of approximately 1°. The stimuli consisted of a bright green area filling the outline of a bright white square on a black background and were viewed under normal room illumination. The response keys were part of the keypad of a normal AT-like keyboard.

Six subjects were simultaneously tested in six sound-attenuated 2.4 x 2.5 x 2 m rooms. There they sat in front of a table on which the keyboard and a computer monitor were positioned. They were monitored by way of a video circuit.

2.4 **Subjects**

Subjects were 36 paid students (initially 15 males and 21 females) from Utrecht University. Eighteen subjects were randomly assigned to each of the two structure conditions. They were paid 90 Dutch guilders for participation. Six subjects in each group received a bonus of 25 guilders. Four subjects were replaced (3 males and 1 female): one because of illness, two because of data loss and one because of extremely poor performance. They were replaced by four additional subjects (2 males and 2 females).

3 RESULTS

Analyses of variance (ANOVAs) were carried out on mean response times per condition, subject, and location of the keypress in the sequence. The analyses generally included response group (i.e. three-, four-, and five-key response group), session, and key-order (depending on the start key in the sequence) as independent variables. Sets of three ANOVAs were used for contrasting response groups: Comparing three- and four-, and three- and five-key groups required between-subjects analyses whereas comparisons of four- and five-key groups was within-subjects. Key-order was included in the analyses to account for effects due to balancing over fingers. Sometimes group-start vs. pooled within-group response times and structured vs. unstructured condition were independent variables as well.

Keypresses involving an error and the two keypresses following that error were discarded from analysis. In each block, the first two trials were considered as warming-up and also discarded. To eliminate outliers individual cut-off values were separately computed for each condition and subject. This eliminated less than 2 percent of the data. An arcsine transformation was carried out on mean error rates per cell before the data were subjected to ANOVAs in order to obtain independence of means and variances (Winer, Brown & Michels, 1991). All ANOVAs on response times showed highly significant main effects of session (all $ps<.001$) which are not separately reported.

3.1 Structured condition

The average response times obtained in the structured blocks of session 1 and 2, and of session 13 and 14 are shown in Fig. 2. In session 1 and 2 a difference is observed between group-start and within-group response times in the three-key group of 333 and in the four-key group of the 45 condition but not in the five-key group of 45. In session 13 and 14 these differences have largely disappeared.

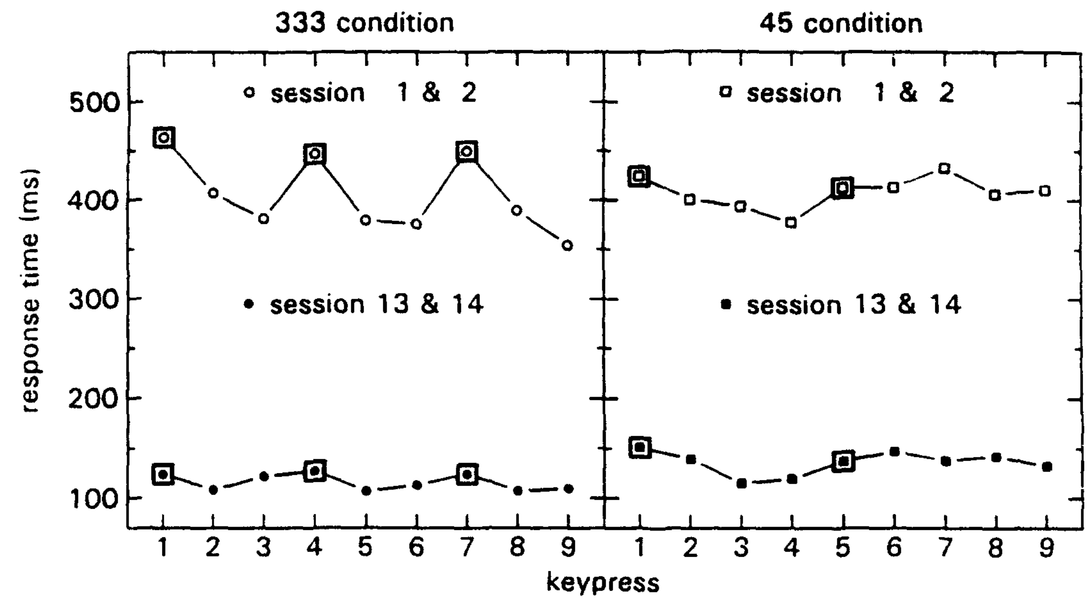

Fig. 2 Response times preceding the individual keypresses in the structured condition as a function of timing structure and level of practice. Additional squares indicate keypresses preceded by a long RSI.

Group-start vs. within-group response times

Three ANOVAs tested the differences between the group-start and pooled within-group response times for three-, four-, and five-key groups separately. In the three-key group the difference between pooled group-start times (T_1, T_4, and T_7) and pooled within-group response times (T_2, T_3, T_5, T_6, T_8, and T_9) amounted to 37 ms [$F(1,9)=51.8$, $p<.001$]. This difference decreased with practice from 72 ms in session 1 and 2 to 14 ms in session 13 and 14 [$F(1,9)=5.3$, $p<.001$]. At the four-key group of 45 the difference (T_1 vs. T_2, T_3, and T_4) amounted to 19 ms [$F(1,18)=3.6$, $p<.10$]. This varied somewhat during practice [$F(13,117)=2.2$, $p<.05$] but was about similar in session 1 and 2, and 13 and 14 (34 vs. 27 ms). Finally, on the average, the response time preceding the five-key group in 45 (T_5) was 10 ms smaller than the pooled within-group response time (T_6, T_7, T_8, and T_9) but this did not reach significance [$F(1,9)=0.9$, $p>.20$]. The difference between group-start and within-group response times did not change with practice (3 ms in session 1 and 2 vs. 2 ms in session 13 and 14).

Three ensuing ANOVAs involved pair-wise comparisons of group-start and within-group response times among groups. They showed that early in practice the three-key group, as a whole, was performed slower than the four-key group and faster late in practice [$F(13,234)=2.6$, $p<.01$]: In session 1 and 2 the average of the group-start and the pooled within-group response times amounted to 417 and 407 ms and in session 13 and 14 118 and 138 ms, resp. The difference between group-start and within-group response times decreased faster with practice for the three- than for the four- and five-key groups: In the three-key group the difference decreased from 72 ms in session 1 and 2 to 14 ms in session 13 and 14 whereas in the four-key group it decreased from 34 to 27 ms [$F(13,234)=2.6$, $p<.01$]. Likewise, the ANOVA comparing three- and five-key groups showed that the reduction in the three-key group (from 72 ms to 14 ms) exceeded the decrease in the five-key group [from 3 ms to 2 ms, $F(13,234)=4.1$, $p<.001$]. The ANOVA comparing four- and five-key groups did not yield this interaction [$F(13,117)=0.9$, $p>.20$].

Group-start times

The presence of a complexity effect in the structured condition was investigated by comparing group-start times of the various response groups. Comparing three- and four-key groups showed a significant interaction between group-start time and practice [$F(13,234)=3.5$, $p<.001$]. The response time preceding the first keypress of the four-key group was about 30 ms less in session 1 and 2 than the one preceding the three-key group and about 26 ms more in session 13 and 14. Planned comparison of response times at day 2 sessions did not show a significant advantage for three-key start times [$F(1,18)=1.1$, $p>.20$]. Likewise, the five-key group was started 41 ms faster than the three-key group in session 1 and 2 and 14 ms slower in session 13 and 14 [$F(13,234)=3.0$, $p<.001$] but this did not yield a significant difference at day 2 sessions either [$F(1,18)=1.0$, $p>.20$]. Finally, the ANOVA comparing the effects of four- and five-key groups showed a main effect of group-size indicating that the time to initiate the four-key group was 15 ms longer than the time to initiate the five-key group [213 vs. 198 ms, $F(1,9)=6.2$, $p<.05$].

Within-group response times

ANOVAs comparing pooled within-group response times showed trends that within-group times were longer in five- than in three- and four-key groups [209 vs. 177 ms, $F(1,18)=3.2$, $p<.10$; 209 vs. 195 ms, $F(1,9)=3.9$, $p<.08$]. In three- and four-key groups within-group times did not differ significantly [177 ms vs. 195 ms, $F(1,18)=1.0$, $p>.20$].

Error analysis

Average error proportions were 4.2 percent in 333 and 5.5 percent in 45 [$F(1,18)=4.3$, $p<.06$]. A structure x session interaction [$F(13,234)=2.5$, $p<.01$] indicated that errors decreased in 333 (session 1 and 2: 4.7%, session 13 and 14: 3.8%) and not in 45 (5.3% and 5.6%, resp.).

In summary, the time taken to start a three-key group was longer than the within-group response times but this difference reduced with practice. In the four- and five-key groups of 45 the differences between group-start and within-groups response times were not significant. As a whole (i.e. after pooling group-start and within-group response times), the three-key groups profited more from practice than the four-key group. The distinction between group-start and within-group response times decreased more with practice in the three-key groups than in the four- an five-key groups. Also, the time to initiate the four- and five-key groups reduced less with practice than the three-key group-start times so that early in practice more time was required to initiate the three-key than the four- and five-key groups whereas this reversed with practice. The four-key group took more time to initiate than the five-key group irrespective of the amount of practice. Within-group response times tended to be longer in five- than in three- and four-key groups. Error rate decreased in 333 but not in 45.

3.2 Unstructured condition

Figure 3 shows that the timing structure in the structured condition determined response times in the unstructured condition. The grouping effect increased with practice in that the difference between group-start times and within-group response times increased with practice.

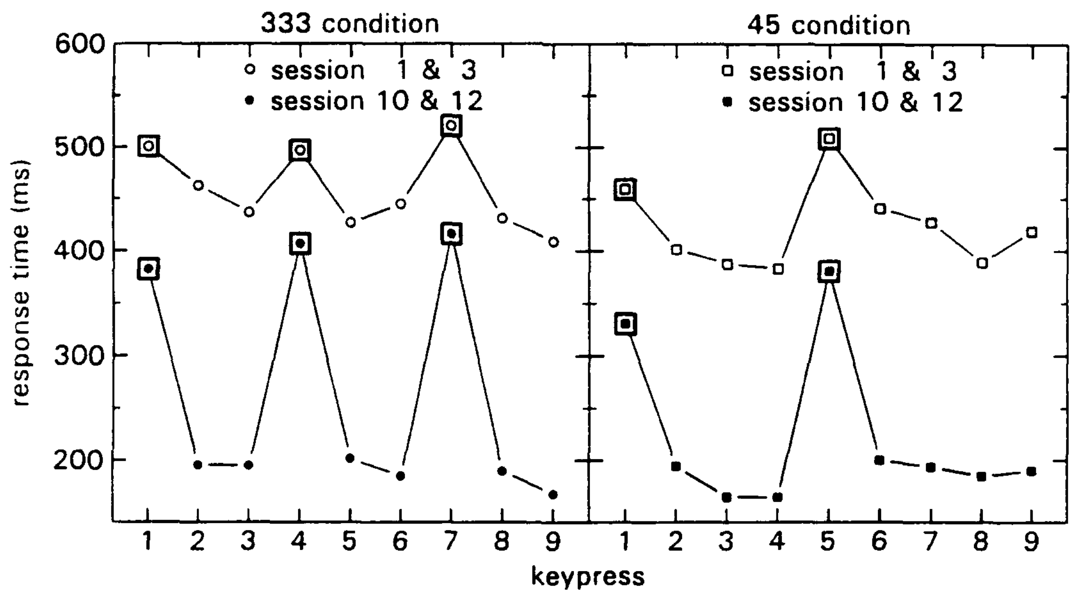

Fig. 3 Response times in the unstructured condition as a function of timing structure in the structured condition and practice. Additional squares indicate response times associated with long RSIs in the structured condition.

Group-start vs. within-group response times

Three ANOVAs were performed on group-start and pooled within-group response times in each response group. All showed significant main effects of group-start vs. within-group response times [three-key group: $F(1,9)=25.8$; four-key group: $F(1,9)=32.4$; five-key group: $F(1,9)=61.5$, all $ps<.001$]. Interactions between group-start vs. within-group and session were also generally found [$F(5,45)=15.0$; $F(5,45)=4.2$; $F(5,45)=7.5$, all $ps<.001$] indicating that the difference between group-start and within-group response times increased with practice.

Pair-wise comparisons of the three groups showed that the differences between group-start and within-group response times were similar in the various groups. Only a significant advantage for the total four- as compared to the five-key group showed that the four-key group was carried out faster than the five-key group: Average group-start and within-group response times amounted to 327 vs. 361 ms [$F(1,9)=10.5$, $p<.01$]. Also, the total four-key group tended to be executed faster than the total three-key group [327 vs. 373 ms, resp., $F(1,18)=3.5$, $p<.08$].

Group-start times

Paired comparisons of group-start times showed a significantly shorter group-start time for the four- than for the five-key group [384 ms vs. 431 ms, resp., $F(1,9)=6.9$, $p<.05$] and a trend that the four-key group was initiated faster than the three-key group [384 ms vs. 448 ms, resp., $F(1,18)=3.7$, $p<.08$].

Within-group response times

Comparisons of the within-group response times showed that the interkey response times within the four-key group were faster than those within the five-key group [271 vs. 292 ms, $F(1,9)=5.1$, $p<.05$]. Those in three- and four-key groups, and three- and five-key groups did not differ significantly [$F(1,18=1.0$; $F(1,18)=0.5$, both $ps>.20$].

Ratios

Figure 4 demonstrates that in all conditions the ratio between group-start and within-group response times increased with practice [three-key group: $F(5,45)=9.2$; four-key group: $F(5,45)=13.7$; five-key group: $F(5,45)=8.1$, all $ps<.001$]. In the last unstructured sessions the ratio exceeded 3:1 in the 333 condition and was well over 2:1 in the 45 condition. Pair-wise comparisons of the individual ratios per session showed that the interactions between group-size and session did not reach significance [three- vs. four-key group: $F(5,90)=1.7$, $p=.13$; three- vs. five-key group: $F(5,90)=1.83$, $p=.11$; four- vs. five-key group: $F(5,45)=0.3$, $p>.20$]. When pooling four- and five-key ratios a marginally significant interaction between structured condition and session [$F(5,90)=2.02$, $p=.08$] was found suggesting that the ratio increased more in 333 than in 45.

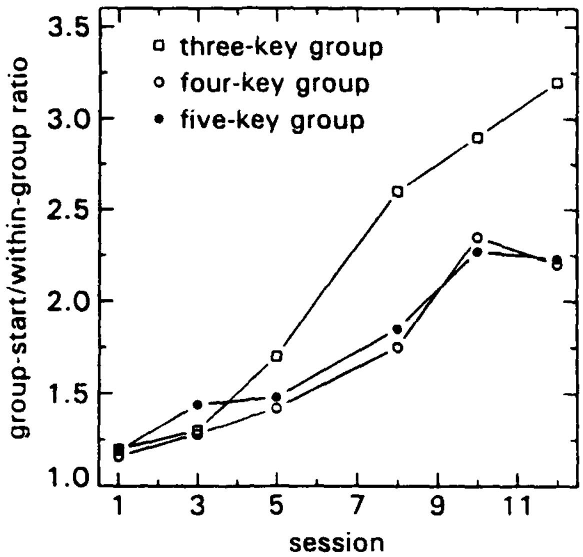

Fig. 4 The ratios between response times preceding groups and those within groups in the unstructured condition as a function of timing structure and level of practice.

Errors

Average error percentage amounted to 7.3% in 333 and 7.7% in 45. This difference was not significant [$F(1,18)=0.8$, $p>.20$] nor were any other effects in the error analysis.

In summary, response times in the unstructured condition associated with long RSIs in the structured condition were longer than response times associated with zero RSIs in the structured condition. The differences between these long and short response times increased with practice and, consequently, so did the group-start/within-group ratio. This ratio clearly exceeded 2:1 with practice and tended to rise faster for three- than for four- and five-key groups. In addition, the total four-key group was performed faster than the total three- and five-key groups which effect appeared to have been due to group-start times and, regarding four- and five-key groups, also to within-group response times.

3.3 Unstructured vs. structured conditions

Group-start times

To compare the time to start each response group in the structured and in the unstructured condition ANOVAs were carried out on the structured and unstructured blocks of the sessions that involved both conditions. Group-start times were found to be smaller in the structured than in the unstructured condition [three-key groups: 247 vs. 448 ms, $F(1,9)=100.0$; four-key group: 245 vs. 384 ms, $F(1,9)=50.1$; five-key group: 231 vs. 431 ms, $F(1,9)=230.5$; all $ps<.001$]. Also, the effect of practice on group-start times was bigger in the structured than in the unstructured condition [difference of session 1 and 12 in the three-key group: 402 vs. 155 ms, $F(5,45)=40.7$; in the four-key group: 364 vs. 204 ms, $F(5,45)=11.3$; and in the five-key group: 373 vs. 185 ms, $F(5,45)=20.9$; all $ps<.001$].

Pair-wise comparison of the effects among group-sizes showed that the difference in group-start times between the structured and the unstructured condition was larger for three- than for four-key groups [201 vs. 139 ms, $F(1,18)=4.8$, $p<.05$] which effect tended to increase with practice [$F(5,90)=1.94$, $p<.10$]. Also, the difference between group-start times in the structured and the unstructured condition was larger for five- than for four-key groups [200 vs. 139 ms $F(1,9)=10.4$, $p<.01$]. Finally, no difference between group-start times in the three- and the five-key group was obtained [$F(1,18)=0.3$, $p>.20$]. Hence, when the 750 ms RSIs in the structured condition were reduced to zero in the unstructured condition, the time to initiate the four-key group increased less than the time to initiate the three- and five-key groups.

Within-group response times

Within-group response times in the structured and the unstructured condition were also compared with an ANOVA for each group-size. Within-group response times were smaller in the structured than in the unstructured condition (three-key group: 204 vs. 298 ms, $F(1,9)=44.5$; four-key group: 222 vs 271 ms, $F(1,9)=71.3$; five-key group: 236 vs. 292 ms, $F(1,9)=95.4$; all $ps<.001$] and decreased more with practice in the structured than in the unstructured condition [difference between session 1 and 12 in the three-key group: 361 vs. 312 ms, $F(5,45)=23.5$; in the four-key group: 363 vs. 283 ms, $F(5,45)=40.6$; in the five-key group: 372 vs. 294 ms, $F(5,45)=25,2$; all $ps<.001$].

The difference between within-group response times in the structured and the unstructured condition was larger in the three- than in the four- and five-key groups but was similar for four- and five-key groups: The differences in the three- and four-key group were 94 and 49 ms [$F(1,18)=8.4$, $p<.01$], in the three- and five-key group 94 and 56 ms [$F(1,18)=6.1$, $p<.05$], and in the four- and five-key group 49 and 56 ms [$F(1,9)=1.3$, $p>.20$].

Summing up, the group-start and within-group response times were clearly larger in the unstructured than in the structured condition for all group-sizes and this difference increased with practice. The difference between initiation time of the first keypress in each group in the structured and unstructured condition was less in the four- than in the three- and five-key groups. Also, the difference between within-group response times in structured and unstructured conditions was less in four- and five-key groups than in three-key groups.

3.4 Individual differences

Examination of the data for individual subjects showed large individual differences. The group-start/within-group ratios in the last session of the unstructured condition ranged from 1.0 to 8.6 in 333 and from 0.9 to 6.5 in 45. A scatter plot of the ratios obtained in the structured vs. those in the unstructured condition showed that subjects with a large group-start/within-group ratio in the last two sessions of the unstructured condition also demonstrated a relatively large ratio in the structured blocks of these sessions whereas subjects with relatively small ratios in the unstructured condition had small or intermediate ratios in the structured condition. This was corroborated by correlations between the ratios in both conditions (333: $r=.42$, $p<.09$; 45: $r=.33$, $p>.15$; together: $r=.32$, $p<.06$). Moreover, individual group-start/within-group ratios in the unstructured condition correlated negatively with individual within-group response times (333: $r=-.55$, $p<.05$; 45: $r=-.44$, $p<.07$; together: $r=-.49$, $p<.01$). Such a relationship was not found between the individual ratios and the individual group-start times (333: $r=-.33$, $p>.15$; 45: $r=.06$, $p>.20$; together: $r=-.23$, $p>.15$). These observations suggest that subjects who used the timing structure to partition the sequence in response groups in the structured condition, had smaller within-group response times and larger ratios in the unstructured condition than subjects who had not partitioned.

4 DISCUSSION

As pointed out in the introduction the results of this study bear on three issues: (1) sequence reproduction by way of natural rhythm vs. motor chunking, (2) concurrent processing in unstructured sequence production, and (3) the occurrence of the complexity effect in structured sequence production.

4.1 Natural rhythm vs. chunking

Consistent with the natural rhythm hypothesis, the RSI pattern in the structured 333 condition determined the response times between succeeding keypresses in the unstructured condition. This replicated Summers' (1975) data. But the natural rhythm hypothesis was unable to predict the response times in the unstructured 45 condition. Moreover, the ratios obtained in 45 did not match a binary tree representation for either sequence. The group-start/within-group response times did not adhere to 2:1 ratios but increased from about 1:1 to over 3:1 in 333 and to over 2:1 in 45. For some subjects the ratio even developed up to 8:1 in 333 and up to 6:1 in 45. The present data, therefore, violate the natural rhythm hypothesis.

The data are more consistent with the view that motor chunks developed. Response times in the unstructured condition mimicked the RSI patterns in the structured 333 as well as in the structured 45 condition. The difference between group-start and within-group response times increased with practice affirming the view that subjects increasingly selected and programmed the keypresses as a group before initiating the first element of that group. The finding that grouping also occurred in the 45 condition indicates that keypressing chunks can contain more than the two or three elements suggested by research on language and music production (Gordon & Meyer, 1987). It is important to note that subjects showed highly consistent individual response patterns in the structured and unstructured conditions, some reacting strongly to the timing structure while others did not react at all. On the one hand this suggests that it was indeed the tendency to execute keypresses in groups in the structured condition that induced the development of motor chunks. On the other hand, the finding that not all subjects used the timing structure for partitioning suggests that future studies should use more explicit ways to force subjects to break up the movement sequence into groups. One may, for example, instruct subjects explicitly to execute keypresses as groups or one may increase the temporal separation between response groups by practicing them in complete isolation.

An interesting question for future research is when chunks are used and how robust they are. And, will the existence of chunks interfere with performance of sequences that deviate slightly from the ones controlled by a chunk? In a recent study (Verwey, 1990) subjects practiced a two-key sequence to a considerable extent. In a predictive condition the first key always predicted the second one, which was assumed to promote the development of motor chunks and, therefore, to reduce performance in an unpredictive transfer phase in which the first response did not predict the second one. This was not found. Subjects appeared to be quite capable of switching from the predictive to the unpredictive sequence. In contrast, the present study shows evidence for chunking in a situation in which there was actually little time for preparation of the response groups. Perhaps, the existence of chunks does not show up when there is ample time for preparing a movement sequence whereas they emerge in situations of time stress. Further research should test this possibility.

Finally, the results have an interesting consequence for the features of a motor program. Summers (Summers, 1975; Summers et al., 1984) and Schmidt (1987) stated that relative timing is an invariant property of a motor program representation. However, the present data, together with Sternberg et al.'s (1990) view that typing and speech sequences only involve two hierarchical levels, suggest that highly practiced sequences involve a concatenation of more or less fixed chunks. Hence, relative timing specifies the boundaries *between* motor programs, each controlling a separate chunk, rather than being part of one motor program.

4.2 Concurrent processing in the unstructured condition

Another issue concerned the extent preparing a response group could concur with executing the previous group in the unstructured condition. The data support this notion since (1) within-group response times were longer in the unstructured than in the structured condition—i.e. reflecting interference—and (2) practice had a smaller effect on within-group response times in the unstructured conditions than in the structured conditions. One could expect that, ultimately, all preparation of a forthcoming response group concurred with the preceding response group. In that case group-start times would reduce to the within-group response time durations. The data show that this is not what happened and that concurrent processing remains a second-order effect.

The data in the unstructured condition show that the three-key response group was initiated slower than the four-key group which is the reverse of the complexity effect. This finding is consistent with the notion that there is more concurrent processing as the preceding response group is longer (Verwey, submitted). The three-key group was preceded by another three-key group while the four-key group was preceded by a five-key group. Further evidence for more concurrent preparation of the four-key group comes from the observation that when the 750 ms RSI was reduced to zero in the unstructured condition, group-start times increased more at the three- than at the four-key group: It seems easier for the four-key group to shift preparation to the execution phase of the preceding response group than for the three-key group. For the five-key group it is not clear whether the relatively slow initiation and execution times were caused by the complexity effect or by concurrent preparation for the four-key group. This issue can be investigated more thoroughly by manipulating the size of the preceding response group between groups while retaining the size of the next group. In any case, the present data provide evidence that part of the preparatory processes required for individual response groups concurred with execution of preceding groups. This delays execution of those groups. Earlier findings (Verwey, submitted) have shown that the slowing effect of concurrent response selection on keypressing rate disappears with practice. The fact that slowing did not disappear with practice in the present study suggests that other processes than response selection concurred with execution of the response groups such as motor programming or motor adjustment (Sanders, 1990; Spijkers, 1990).

4.3 The complexity effect in the structured condition

The complexity effect was about absent in the structured condition. In itself this argues against the view that the response groups are selected, programmed and executed in the same way as isolated sequences (Henry & Rogers, 1960; Sternberg et al., 1978). It could well be that preparing a new response group starts already while executing the preceding response group—that is, before the start of the 750 ms RSI. Two findings suggest that preparatory processing also concurred with execution of the preceding response group in the structured condition. First, a larger practice effect was observed on group-start times for three-key groups than for four- and five-key groups. Second, a larger practice effect was observed for the difference between group-start and within-group response times at the three- as compared to the four- and five-key groups. Together these findings suggest that, early in practice, four- and five-key groups could be more prepared during execution of the preceding response group than three-key groups which is ascribed to the longer preceding response groups in 45 than in 333. However, with practice, the time required to start the three-key group reduced (Hulstijn & Van Galen, 1983; Verwey, in press-1, in press-2) so that the 750 ms RSI became sufficient for preparing the three-key group. Hence, the group-start times in 333 dropped more with practice than those in the 45 condition. This reasoning is supported by the observation that error rate reduced with practice in 333 but not in 45. So, the data suggest that the complexity effect did not notably occur in the structured condition because the 750 ms RSIs did not eliminate confounding of the complexity effect and concurrent preparation. The suggestion that 750 ms did not suffice to complete preparation is plausible when considering that RSIs of over 1000 ms did not completely eliminate interactions between sequential responses (Noble, Sanders & Trumbo, 1981; Noble & Sanders, n.d.). It seems that the total of specific and aspecific preparation for a response group requires a substantial amount of time—in the present study over 750 ms early in practice. Further research is required to study this more directly.

Summing up, the present study favors the notion that practice in a sequential movement task invokes motor chunks when a timing structure is imposed during prolonged practice. The view that mechanisms underlying rhythmic performance also determine performance in unstructured conditions is rejected. Notions of concurrent processing can account for the detailed pattern of the results: As the preceding response group was longer concurrent preparation occurred with less practice and to a higher degree. However, concurrent preparation did also delay execution of the ongoing response group. So, two mechanisms appear to influence chunk-start and within-chunk response times: From earlier research it is known that the number of elements in a sequence increases group-start times. But preparation for a chunk during execution of the preceding group reduces chunk-start times and increases within-group response times of the preceding chunk. Future research should establish the robustness of motor chunks in other conditions and should further investigate which processes can concur with and without mutual interference.

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Soesterberg, June 22, 1993

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Drs. ~~Ing.~~ W.B. Verwey

REPORT DOCUMENTATION PAGE

1. DEFENCE REPORT NUMBER (MOD-NL) TD 93-1348	2. RECIPIENT'S ACCESSION NUMBER	3. PERFORMING ORGANIZATION REPORT NUMBER IZF 1993 B-6
4. PROJECT/TASK/WORK UNIT NO. 788.2	5. CONTRACT NUMBER B92-26	6. REPORT DATE 22 June 1993
7. NUMBER OF PAGES 24	8. NUMBER OF REFERENCES 40	9. TYPE OF REPORT AND DATES COVERED Final

10. TITLE AND SUBTITLE

On the development of motor chunks and concurrent processing in a structured continuous keypressing task

11. AUTHOR(S)

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12. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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Schoemakerstraat 97
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14. SUPPLEMENTARY NOTES

15. ABSTRACT (MAXIMUM 200 WORDS, 1044 BYTE)

This report describes an experiment designed to assess the effects of practice in performing a structured sequence of keypresses. The task consisted of pressing a sequence of nine keys with nine fingers, each in response to a corresponding stimulus. Each response was followed by a response-stimulus interval (RSI), which sometimes was zero ms, before the next stimulus was presented. Upon completion of one sequence, production of the identical sequence was immediately repeated. One group of 18 subjects-the 333 group-practiced with three regularly spaced, non-negligible, response-stimulus intervals (RSIs) while the remaining RSIs were zero. This divided the sequence into three groups of three keypresses each. Another group of 18 subjects-the 45 group-practiced with two non-negligible RSIs partitioning the sequence into a four- and a five-key group. These conditions were coined structured conditions. On occasion all subjects carried out a condition in which all RSIs were zero. This was the unstructured condition. The results show that interkey times in this condition clearly reflected the position of the long RSIs in the structured condition. This suggests that motor chunks had developed in the structured condition which were also used in the unstructured condition. More detailed analyses suggest that preparing one chunk concurred with execution of the preceding chunk in the unstructured and probably also in the structured condition. Concurrent preparation of the next chunk slowed down execution of the preceding chunk in the unstructured condition. In the structured condition it concealed effects of chunk-size on initiating each chunk (i.e. the complexity effect).

16. DESCRIPTORS	IDENTIFIERS
Perceptual Motor Skills Reaction Time	

17a. SECURITY CLASSIFICATION (OF REPORT)	17b. SECURITY CLASSIFICATION (OF PAGE)	17c. SECURITY CLASSIFICATION (OF ABSTRACT)
18. DISTRIBUTION/AVAILABILITY STATEMENT Unlimited availability		17d. SECURITY CLASSIFICATION (OF TITLES)

VERZENDLIJST

1. Hoofddirecteur van TNO-Defensieonderzoek
2. Directie Wetenschappelijk Onderzoek en Ontwikkeling Defensie
3. { Hoofd Wetenschappelijk Onderzoek KL
   Plv. Hoofd Wetenschappelijk Onderzoek KL
4. Hoofd Wetenschappelijk Onderzoek KLu
5. { Hoofd Wetenschappelijk Onderzoek KM
   Plv. Hoofd Wetenschappelijk Onderzoek KM

6, 7, 8. Hoofd van het Wetensch. en Techn. Doc.- en Inform. Centrum voor de Krijgsmacht

Extra exemplaren van dit rapport kunnen worden aangevraagd door tussenkomst van de HWOs of de DWOO.